International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249-6890; ISSN(E): 2249-8001
Vol. 9, Issue 4, Aug 2019, 71-82

OFFSETTING OF CIRCULAR CROSS BORE EFFECTS ON ELASTIC PRESSURIZED THICK CYLINDERS

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ABSTRACT

A research to determine an optimal location of a circular cross bore in thick walled high pressure vessels was conducted. Cylinders of thickness ratios of 3.0 down to 1.4 with circular cross bore at varying offset position were studied. The effects of a small circular cross bore, having cross bore to main bore size ratio of 0.1 was studied at nine different offset locations. It was established that offsetting of circular shaped cross bores appropriately reduces the magnitude of Stress Concentration Factors (SCFs). Among the nine offset positions studied, the minimum SCF magnitudes occurred between offset location ratios of 0.685 and 0.9. Besides, the optimal location was found to be at 0.9 offset position at the thickness ratio of 1.4, with a SCF magnitude of 2.312. This SCF magnitude indicated a reduction of pressure carrying capacity of 56.7% in comparison to a similar plain cylinder without a cross bore.

KEYWORDS: Pressure Vessels, Circular Cross Bores, Location, Finite Element Analysis & Stress Concentration

Received: Apr 06, 2019; **Accepted:** Apr 26, 2019; **Published:** Jun 17, 2019; **Paper Id.:** IJMPERDAUG20198

Original Article

INTRODUCTION

High pressure vessels are air tight containers [1] that are used to store large amounts of energy [2]. They are used for numerous applications in steam and nuclear power plants, process and chemical plants, sea mining, simulation of deep ocean and down well, industrial and domestic gas cylinders, among others[3-4].

Holes or openings are made in the wall of plain pressure vessels [5] to give provision for fitting essential operation and maintenance accessories. These accessories include relief and safety valves, bursting discs, gas inlets, flow circuit meters, temperature and internal pressure measurement, inspection covers and lubrication [2]. Whenever these openings are placed at the transverse position in both sides of the vessel, they are referred to as cross bores [6-7]. Different cross bores sizes and shapes are used in the design of pressure vessels. The size of the cross bore ranges from small nozzles to large manholes like tee junctions [3]. Besides, only circular and elliptical shapes cross bores are commonly used in pressure vessel design [8].

Whenever a cross bore is constructed at the central axis of the vessel it is termed as radial cross bore. Alternatively, when a cross bore is placed at any other chord away from the central axis of the cylinder it is referred to as an offset cross bore [7]. The offset distance of the cross bore is measured between the transverse plane of the cross bore and the central axis of the vessel. However, the offset distance is converted to either offset location ratio or included angle for effective comparison of results with other studies. Whilst, the trigonometric relationship between the two distances is used to determine the included angle.

Drilling of cross bores in the wall of the vessel introduce geometric discontinuities that alter the uniform stress distribution [5].Subsequently, these geometric discontinuities act as stress raisers, which create regions of high stress concentration especially along the cross bore depth. Nonetheless, high magnitudes of stress concentration are associated with persistent problems in the design of pressure vessels such as fractures, fatigue and local yielding [7].It is, therefore, necessary to design for an optimal minimum hoop stress concentration in order to reduce the occurrence of these problems.

Cheng [9] investigated experimentally using photo elastic method different circular cross bore sizes, with size ratios (cross bar to the main bore ratio) of 0.05, 0.1 and 0.2 at various off-site locations in a thick cylinder. The thick cylinder which was studied had a thickness ratio of 1.84. For the cross bore size ratio of 0.05, the SCFs were investigated at the offset positions of 0.317 and 0.633. While, for the cross bore size ratio of 0.1, the SCFs were studied at offset positions of 0.3 and 0.6. Lastly, the SCFs for cross bore size ratio of 0.2 were studied at offset positions of 0.267 and 0.533. This study concluded that off setting a circular cross bore leads to significant reduction of SCFs.

Masu [5] investigated the effects of offsetting small circular cross bores in thick walled cylinder with a thickness ratio of 2, using finite element method. SCF reductions of 17 % and 42% were reported, when the cross bore was positioned in an offset ratio of 0.24 and 0.9, respectively, from the radial line. A similar work had been done experimentally by Cole *et al.* [10]. Noticeably, the findings of the two studies cited in this paragraph were in good agreement.

Makulsawatudom *et al.* [7] studied the effects of small circular and elliptical shaped cross bores on stress concentration in thick cylinders using finite element analysis. The thickness ratios of the cylinders were between 1.5 and 2.5. Both the two shapes of the cross bores were investigated at radial and offset positions. Unfortunately, only one single offset position was studied. The study concluded that the lowest magnitudes of SCF occur at the radial elliptical plain cross bores.

From the preceding paragraphs, it is evident that SCF in cross bored pressure vessels reduces whenever a circular cross bore is positioned in an offset position. However, studies on optimal location of a circular cross bore have not been fully investigated. Therefore, the aim of this study was to determine an optimal location of a circular cross bore in thick walled high pressure vessels

METHODOLOGY

Closed thick cylinders of thickness ratios of 3.0 down to 1.4 with circular cross bore placed at various offset and radial positions were studied. Seven cylinders with thickness ratios of 1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0 were modelled. Throughout this study, both the size of the main bore and the cross bore were kept constant. The main bore diameter was 0.05 m. While a circular cross bore with size ratio (cross bore to main bore ratio) of 0.1 was used.

A total of nine locations (radial and various offset positions) were investigation in each of the seven cylinders. The locations were obtained by offsetting a circular cross bore at different positions along the radial X axis of the cylinder as shown in Figure 1.

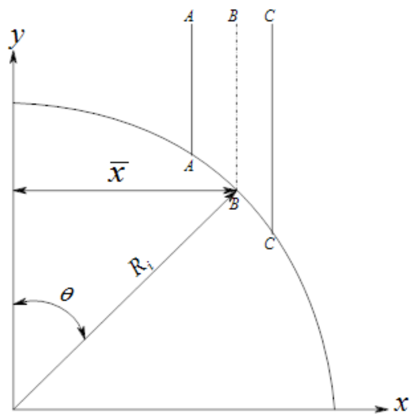

Figure 1: Configuration of an Offset Cross Bore

The offset location ratio was calculated by dividing the actual offset distance$\bar{x}$, with the main bore radiusR_i, i.e., $\bar{x}/R_i$, as shown in Figure 1. The exact location ratios investigated included 0, 0.12, 0.24, 0.36, 0.48, 0.58, 0.685, 0.79 and 0.9. The offset ratio of 0.48 and 0.9 were similar to those studied by Masu [5] and Cole *et al.* [10]. Whereas, the other offset ratios were chosen arbitrarily at the mid location to investigate the stress behaviour at those points. Besides, the included angle θcan be calculated using the trigonometric relationship between $\bar{x}$ and R_i for all the positions.

THREE DIMENSIONAL FINITE ELEMENT ANALYSIS

Finite element analyses were performed using a commercial engineering software called Abaqus version 6.16 on both radial and offset circular cross bores. The Abaqus software was chosen for this study due to its availability as well as the capability to perform axisymmetric modelling in pressure vessels. For the entire work, a total of 63 different part models were investigated.

Since the structure of the cylinder is symmetrical, only an eighth of the structure was analysed. Deformable solid structure in three dimensional form was created by sketching an eighth profile of the pressure vessel face. The depth of the cylinder was then formed by extruding the sketched face of the cylinder. As stated by the Saint-Venant's principle, the depth of the cylinder should be 2.5 times longer than the outside diameter. This restricts the effects of the closed ends' closures of the cylinder vessels from being transmitted to the other far end of the cylinder. Therefore, a depth equal to three times the cylinder's external diameter was chosen.

The cross bore was then created at the other far end of the cylinder. The offset cross bores were formed by using cut revolve tool technique, while applying full boundary drawing constraints on the cross bore. One of the model profiles created at this stage is shown in Figure 2.

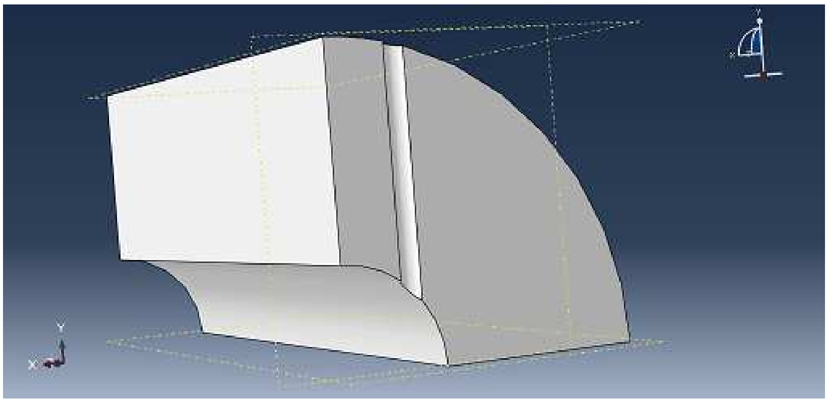

Figure 2: Selected Profile of The Model

The material properties outlined in Table 1 were used for the entire analyses under elastic static conditions. The choice of these material properties were made to coincide with those recommended in the technical literature in the design of pressure vessels

Table 1: Material Properties for the Static Analysis

Parameter	Value
Young’s Modulus of Elasticity	190 GPa
Poisson’s ratio	0.29
Density	7800 Kg/m^3

The model properties were defined as being solid and assigned to the entire profile previously created in Figure 2. This action allowed creation of a single model assembly. A single model assembly usually contains all the geometry in the finite element model. This procedure was then followed by creation of a part instance which was independent of the mesh. The model created was then oriented to conform to the global Cartesian co-ordinates axes that is X, Y and Z axes. Further, the analysis to be used for this simulation was configured by creating a static pressure step.

Boundary conditions were applied at the cut sections of the cylinder to prevent any rigid movement of the model. The boundary conditions of symmetrical type were chosen and applied at each cut sections of the model, in X, Y and Z axes. The vessel was then loaded with an internal pressure of 1 MPa, at both the main bore and the cross bore. In addition, uniform axial stress$\sigma_z$was calculated for each thickness ratio using equation (1). The calculated axial stresses were then applied at the far end in each corresponding vessels to simulate the effects generated by the end enclosures.

$$\sigma_z = \frac{p_i}{K^2 - 1} \tag{1}$$

Where

P_i is the internal pressure.

K is the thickness ratio

The meshing of the model was done by dividing the created part into small geometrical sections. The mesh around the cross bore region was biased by increasing the number of elements, commonly referred to as mesh density. The mesh was found to converge whenever the size of the elements were between 0.003 m and 0.004 m. It is worthwhile noting that the high mesh density around the cross bore region increases the capture of the localised stress concentration.

In line with Abaqus software guideline, only second order hexahedral and tetrahedral elements are recommended for any stress concentration problems. Hence, only second order C3D10 tetrahedral elements with 10 nodes were used for meshing. Usually, the rate of distortion of tetrahedral elements is low, since their elements are less sensitive to their initial shape. A meshed profile of one of the model part is shown in Figure 3.

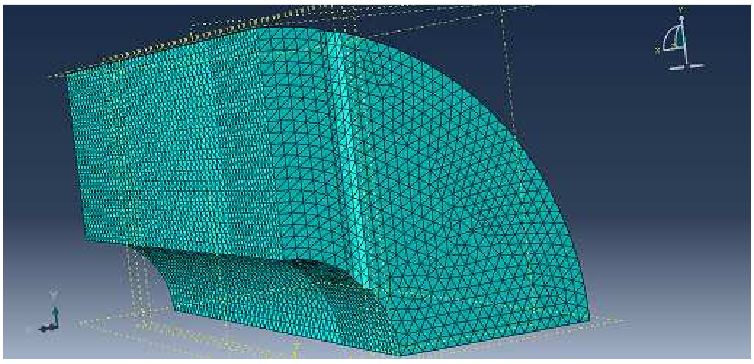

Figure 3: Selected Profile of the Mesh

VALIDATION OF THE MODEL

The accuracy of results given by finite element modelling depends on the quality of the mesh and its density. Generally, element distortion leads to erroneous results. Thus, to eliminate the occurrence of any element distortion, the percentage tolerance for both the element warnings and errors were kept at zero.

The validation of the model was achieved through two stages. In the first stage, the authentication of the results as well as the mesh convergence, were done by comparing the FEA strains and stresses, with their corresponding analytical results in areas far away from the cross bore [12]. According to Saint-Venant's principle the effects of any discontinuity is limited to its surrounding area. For a cross bore, the effects are limited to the surrounding region, approximated to be linear length of 2.5 cross bore diameters. Whereas, in the second stage, the existing published data on related work was compared with results from the current study [12]. The error margin between published work and the present study was kept below 5% in accordance with most practical engineering design applications.

STRESS CONCENTRATION FACTOR

The theoretical Stress Concentration Factor (SCF) was defined as the ratio of localised critical stresses in a cross bore cylinder to the corresponding one in a similar cylinder without a bore. The SCFs were calculated based on locations with the highest magnitudes of hoop stress in the cylinder. It is important to mention that fatigue crack and failures start at the surface of the component with high magnitudes of hoop stresses. Besides, in most engineering works, the design strength is based on the highest stress magnitudes.

RESULTS AND DISCUSSION

Location of Maximum Principal Stress in the Cylinder

Results profile of one of the selected model showing the location of maximum principal stress at the cross bore intersection is shown in Figure 4.

A brief summary showing the location of maximum principal stress on the cylinder due to the introduction of an offset circular cross bore is tabulated in Appendix 1. The summary is presented in the form of the main cylinder radius and

the corresponding horizontal distance measured from the transverse plane of the main cylinder.

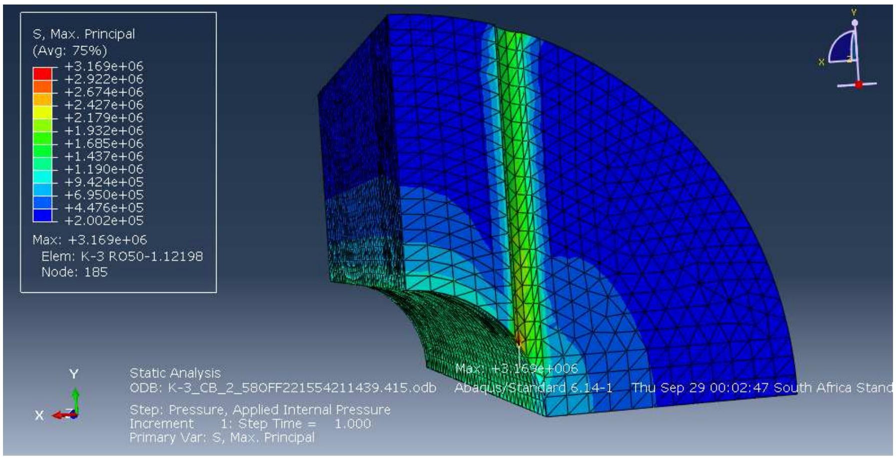

Figure 4: Selected Model Profile Showing Results of Maximum Principal Stress

The radial location of the maximum hoop stress in the cylinder as shown in Appendix 1 occurred mostly at the intersection between the cross bore and the main bore. However, with exception of radial cross bore, the location of maximum principal stress was observed to occur slightly away from the cross bore transverse position in the cylinder. In most of the offset cross bores, the location of maximum principal stress occurred close to plane axis AA (see Figure 1). This observation was contrary to the notion that maximum principal stress occurs along the cross bore transverse position, plane BB. Thus, this occurrence implied that any reduction in offset location ratio results to an increase of hoop stress. This trend confirms that the stress field distribution in the vicinity of cross bore is not uniform whenever the cross bore is at an offset position. Hence the plane stress conditions cease to apply.

Stress peaks occurring slightly away from the cross bore intersection were observed at various thickness ratios in all the offset positions. As noted previously, the location shift of the stress peak was also attributed to the change of state of stress from plane stress to plane strain. Existence of varying magnitudes of bending moments and shearing stress at each offset position due to the curvature of the cylinder also affect the location of the stress peak.

Effects of Cross Bore Location on Hoop Stress Concentration Factor

The curves showing the variation of hoop stress concentration factor with offset location and cylinder thickness ratios are shown in Figures 5 and 6, respectively.

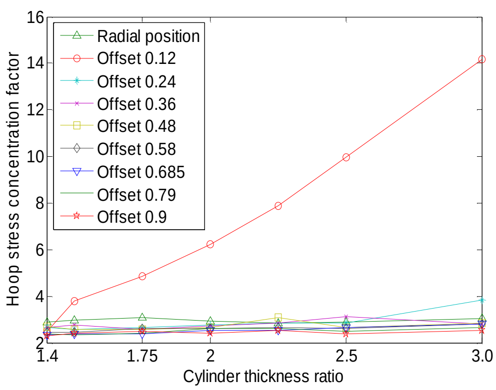

Figure 5: Hoop SCF Vs Thickness Ratio

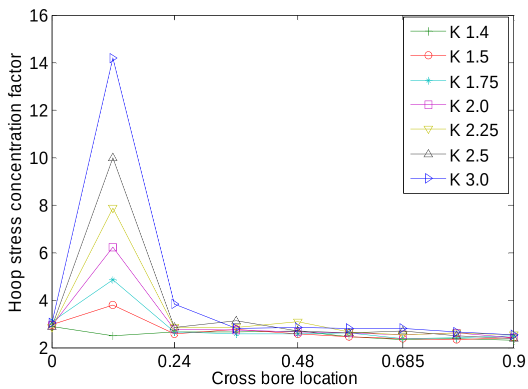

Figure 6: Hoop SCF Vs Cross Bore Location

With exception of 0.12 offset ratio, the effects of offsetting the cross bore on the increase of the thickness ratio was noted to be fairly constant as illustrated in Figure 5. However, at offset ratio of 0.12 the SCF was observed to increase steadily with increase in thickness ratio signifying an existence of transition point.

As observed in Figure 6, the magnitude of hoop stress concentration factor at the radial position (zero offset) ranged from 2.836 to 3.078, occurring at K= 2.25 and 1.75. However, these SCF values recorded at radial position were generally lower than those at the 0.12offset position except for K=1.4. The SCF at K=3.0 had the highest peak magnitude of 14.174. This stress peak was attributed to the formation of an ellipse like shape of the cross bore when viewed at the intersection of the cross bore and the main bore. As shown in Figure 7, the formed ellipse had its major axis perpendicular to the direction of the cylinder axial stress.

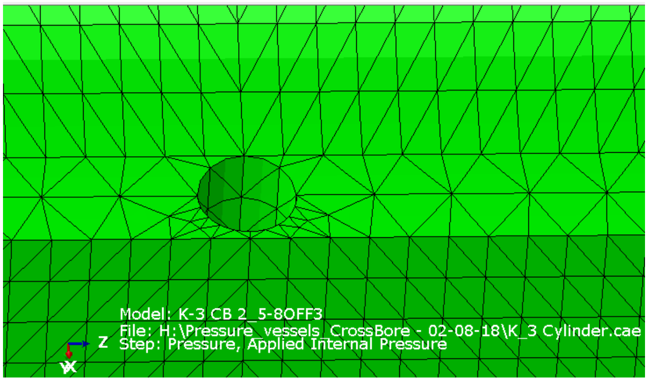

Figure 7: Shape of the Cross Bore at the Intersection of the Main Bore at Offset Ratio of 0.12

Further, the hoop stress concentration magnitude at 0.48 offset position was slightly higher than that of 0.24, for cylinders with K=1.4, 1.5, 2.25 and 2.5. However, for the other thickness ratios, the SCF magnitude was seen to reduce gradually. Notably, the SCF magnitudes given at offset ratios 0.48 and 0.58 were relatively equal.

For all the cylinders studied, the lowest magnitudes of SCF occurred between 0.689 and 0.9 offset positions. For K= 1.75 and 2.25, the minimum SCF were recorded at 0.689 with optimal magnitudes of 2.391, 2.521, respectively. At 0.79 offset ratio, only K = 1.5 had minimum SCF of 2.332. Whereas for K= 1.4, 2.0, 2.5 and 3.0 the minimum SCF occurred at the 0.9 offset position with optimal SCF magnitudes of 2.312, 2.404, 2.365 and 2.535, respectively.

Unlike at the offset ratio of 0.24, the shape of the cross bore obtained at 0.9 offset ratio was slender, with its major axis parallel to the direction of the axial stress. This cross bore configuration is illustrated in Figure 8.

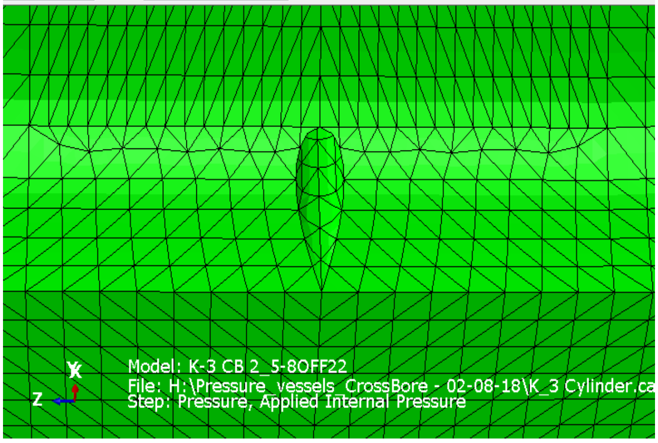

Figure 8:Shape of the Cross Bore at the Intersection of the Main Bore at Offset Ratio of 0.9

Optimal Thickness Ratios and Offset Locations

A graph showing optimal SCF magnitudes that can be obtained at each thickness ratio for an offset circular cross bore is shown in Figure 9.

Likewise, a graph showing optimal SCF magnitudes that can be obtained at each offset position for an offset circular cross bore is exemplified in Figure 10. While, the corresponding thickness ratios at which the lowest SCF magnitude occurred in each of the following offset position; 0,

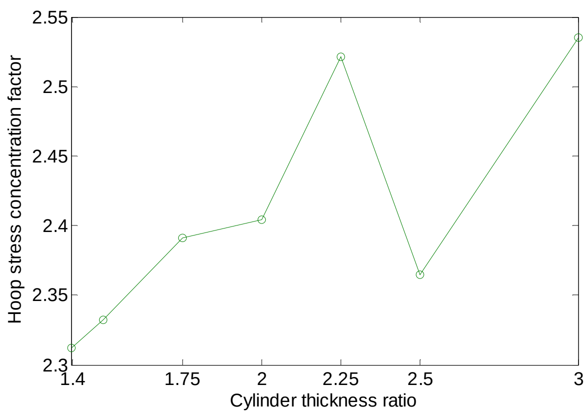

Figure 9: Optimal Hoop SCF Vs Thickness Ratio

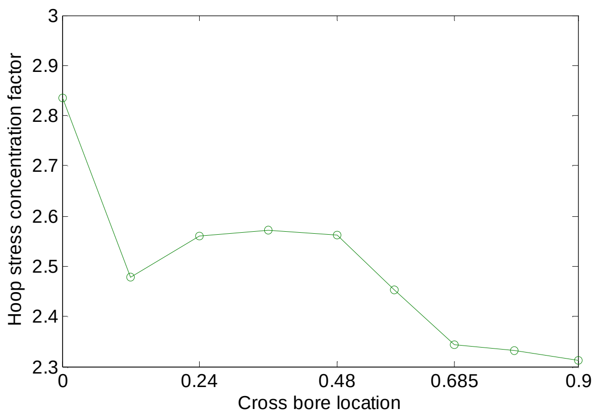

Figure 10: Optimal Hoop SCF Vs Cross Bore Location

0.12, 0.24, 0.36, 0.48, 0.58, 0.685, 0.79 and 0.9 are 2.25, 1.4, 1.5, 1.75, 1.75, 1.5, 1.4, 1.5 and 1.4, respectively.

DISCUSSION OF THE RESULTS

Only the SCF for K=2.0 reduced gradually at the offset positions between 0.24 and 0.9. This observation was in agreement with other previous studies referenced in [5] and [9]. Masu [5] studied slightly smaller circular cross bore sizes, having a size ratio of only 0.064 for K=2.0. Even though the cross bore sizes were smaller, the data presented were generally consistent with the finding of this study. The SCFs presented by Masu [5], considering the offset positions 0, 0.24 and 0.9, were 2.30, 1.9 and 1.33 respectively. This being a reduction of 17.3% and 42.17% from the values at the radial position. However, low SCF reductions of 8.86 % and 17.72% were reported in this study at the same offset position as Masu [5]. These two studies indicated a downward trend in SCFs as a result of circular cross bore offsetting.

Nevertheless, the variation in percentage reduction of the SCFs between the two studies was attributed to the dissimilar sizes of the cross bore sizes studied.

Cheng [9]study further confirmed experimentally that stress concentration reduces by offsetting of a circular cross bore. Analysis of relevant SCF data extracted from this reference [9] is tabulated in Table 2.

Table 2: Analysis of Relevant SCF Data Extracted from Cheng [9] Study

K	Cross Bore Size Ratio	Offset Location Ratio		SCF Reduction (%)
1.84	0.05	0.317	0.633	16.37
1.84	0.10	0.300	0.600	13.57
1.84	0.20	0.267	0.533	16.8

Another study by Makulsawatudom *et al.* [8] erroneously cited Masu [5] that the optimal offset location for all thickness ratio as being 0.112b.Where b was termed as the outer radius of the cylinder. Unfortunately, this study by Makulsawatudom *et al.* [8] had only been done on a single offset position. Therefore, this discussion did not take into consideration the results published by this author on offsetting of circular cross bores.

Further computation was done to establish the highest possible reduction of SCF that can be achieved by offsetting of the cross bore. The computation was based on the maximum and minimum SCF magnitudes obtained at each thickness ratio. The reduction is presented in Table 3.

Table 3: Maximum Possible Reduction in SCF that can be Obtained by Appropriate Choice of Thickness Ratio

K	1.40	1.50	1.75	2.00	2.25	2.50	3.00
SCF reduction %	20.28	38.52	50.82	61.28	67.93	76.30	82.12

Similar approaches were also done at each offset position as tabulated in Table 4.

Table 4: Maximum Possible Reduction in SCF that can Obtained by Appropriate Choice of an Offset Position

Offset ratio	0	0.12	0.24	0.36	0.48	0.58	0.685	0.79	0.9
SCF reduction %	6.30	82.5	33.1	17.8	18.2	13.1	16.6	11.9	10.9

In general, whenever a circular cross bore is drilled in an offset position, the axis of the circular cross bore cylinder does not intersect with that of the main bore. Thus, the resulting configuration, when viewed at the intersection between the cross bore and main bore, resembles a slender elliptical hole with major and minor diameters. The major diameter, denoted as ‘a’ which is parallel to the direction of hoop stress tends to increase when the offset position is moved further away from the transverse plane of the cylinder. Whereas, the corresponding minor diameter, denoted as ‘b’, which is parallel to the axial direction of the cylinder reduces. This diameter configuration where $a > b$ leads to reduction in hoop stress as cited by Harvey [11]. Besides, when an ellipse hole becomes slender or nearer to a crack, the hoop stress in the vicinity of the hole rises rapidly beyond the yield point. Due to these high stresses, the region close to the hole vicinity undergo plastic deformation. This phenomenon results to tremendous reduction of the local stresses.

In summary, the minimum SCF due to the introduction of a circular offset cross bore, with size ratio 0.1, satisfied both the thickness ratio and the offset position conditions coincidently. This optimum location was found to be at 0.9 offset position for K=1.4, with a SCF magnitude of 2.312. This SCF magnitude indicated a reduction of pressure carrying capacity by 56.7% in comparison to a similar plain cylinder without a cross bore. This pressure carrying capacity was

slightly lower than 60% cited earlier by Masu's [12] study.

CONCLUSIONS

Appropriate offsetting of circular shaped cross bores reduces the magnitude of SCFs. Among the nine offset position studied in seven cylinders, the minimum SCF magnitudes occurred between offset location ratios of 0.685 and 0.9. However, the optimum location was found to be at 0.9 offset position for K=1.4, with a SCF magnitude of 2.312. This SCF magnitude indicated a reduction of pressure carrying capacity of 56.7% in comparison to a similar plain cylinder without a cross bore.

LIST OF ABBREVIATIONS

K Thickness ratio (outer diameter to inner diameter)

SCF Stress Concentration Factor

a Major diameter

b Minor diameter

ACKNOWLEDGEMENTS

This research work was supported by Vaal University of Technology. The authors wish to thank the department of Mechanical Engineering at Vaal University of Technology for facilitating this work.

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APPENDIX

Table 5: Location of the Maximum Hoop Stress in the Cylinder due to an Offset Circular Cross Bore

K	Offset Ratio	Actual Offset Distance $\bar{x}$m	Distance of the Cross Bore Configuration Measured from the Transverse Axis of the Main Cylinder			Position of Maximum Principle Stress in the Cylinder (m)	
			Plane AA	Plane BB	Plane CC	Radius R (m)	Horizontal Distance $\bar{x}$, Measured from the Transverse Axis of the Main Cylinder
1.4	0	0		0	0.0025	0.026	0
	0.24	0.006	0.0035	0.006	0.0085	0.025	0.006
	0.48	0.012	0.0095	0.012	0.0145	0.025	0.0111
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.0163
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.0206
1.5	0	0		0	0.0025	0.02625	0
	0.24	0.006	0.0035	0.006	0.0085	0.025	0.006
	0.48	0.012	0.0095	0.012	0.0145	0.025	0.0114
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.0166
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.02061
1.75	0	0		0	0.0025	0.02625	0
	0.24	0.006	0.0035	0.006	0.0085	0.0258	0.006
	0.48	0.012	0.0095	0.012	0.0145	0.025	0.0111
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.01631
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.0206
2.0	0	0		0	0.0025	0.025	0
	0.24	0.006	0.0035	0.006	0.0085	0.025	0.006
	0.48	0.012	0.0095	0.012	0.0145	0.025	0.0111
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.0163
	0.9	0.0225	0.02	0.0225	0.025	0.0253	0.021
2.25	0	0		0	0.0025	0.025	0
	0.24	0.006	0.0035	0.006	0.0085	0.025	0.006
	0.48	0.012	0.0095	0.012	0.0145	0.0265	0.012
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.0163
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.0206
2.5	0	0		0	0.0025	0.0025	0
	0.24	0.006	0.0035	0.006	0.0085	0.025	0.006
	0.48	0.012	0.0095	0.012	0.0145	0.0264	0.012
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.0163
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.02108
3.0	0	0		0	0.0025	0.025	0
	0.24	0.006	0.0035	0.006	0.0085	0.0287	0.006
	0.48	0.012	0.0095	0.012	0.0145	0.025	0.0111
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.0163
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.0211